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TRANSMISSION OF CW PULSES

by

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TRANSMISSION OF CW PULSES*,**

Hudson Laboratories Operation 74

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Technical memo.

Introduction

This is the first of a series of reports relating to the propagation of CW pulses through the ocean. At the present writing three sets of experiments have already been performed. For this reason the discussion will not be strictly chronological. Results of later experiments will be utilized wherever convenient, and post references will be cited.

By a CW pulse we mean a short burst of sinusoidal sound from a source operating at its resonant frequency. Short bursts are used in order to provide isolation of arrivals which have traveled by separate paths, e.g.,

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direct, surface reflected, bottom reflected, and multiply reflected.

To date the experiments have been largely pilot ones to locate interesting phenomena and to determine what parameters are suitable for characterizing the arrivals.

Many theoretical and experimental reports[1-7] have been written concerning these problems and the related ones of continuous wave transmission. All pulsed work referenced herein has been concerned with the propagation of high-frequency ($\geq$ 10 kc) sound waves; moreover, very little has been reported concerning the fluctuations of surface arrivals.

This report is concerned with the transmission and reflection from the surface of low-frequency (126, 148, and 169 cps) sound waves. Two main configurations of source and receiver were used. In the August 1958 experiment (to be referred to as Op. 74) and during phases of the January 1959 (Op. 81) and August 1959 (Op. 91) experiments, the source was within a few wavelengths of the surface, while the receiver was in the deep sound channel. This configuration allowed a study of the superposition of the direct and surface-reflected arrivals, and in particular the effect of the relative phase shift between the two on the energy received at the hydrophone and on the relative fluctuation

$$F = \frac{\text{standard deviation of } \int p^2 \, dt}{[\text{average value of } \int p^2 \, dt]^2} \quad,$$

in which p is the acoustic pressure.

The other configuration of source and receiver, which was used during the rest of Op. 81 and Op. 91, involved both a source and a receiver near the axis of the deep sound channel (2000-3000 ft deep). This allowed a study of the direct arrival, surface-reflected arrival, and bottom-reflected arrival individually, since the differences in travel times along the three

paths were considerably greater than the pulse length.

The three experiments will be presented in separate reports, but their interrelations will be introduced wherever needed.

Experimental Procedure

Operation 74 took place off the coast of Bermuda. Two sets of hydrophones were used: one pair to be designated as C_N and C_S, the other as D_N and D_S. The C pair were bottomed about 150 ft apart in 3840 ft of water. The D pair were bottomed in 1440 ft of water at about 4300 yd from the deep set. Throughout the area the bottom is irregular.

The source, an electromagnetic noisemaker,[8] was suspended at a depth of 55 ft. The CW pulses were produced by gating 15 cycles of a crystal-controlled frequency into the source. This frequency, 148 cps, was chosen to correspond to the resonant frequency of the transducer. The Q of the transducer was kept low so that essentially full amplitude could be reached in 4 or 5 cycles. The pulses were repeated every 6 seconds.

Two of the four signals were filtered through Gertsch filters set to pass a band from 106 to 212 cps and were recorded on a dual channel FM Ampex tape recorder. One channel recorded C_N at all times. The other channel recorded D_N whenever it delivered a signal clearly above background noise. For the rest of the time C_S was recorded.

No monitor hydrophone was mounted near the noisemaker. However, many of the arrivals recorded at short ranges are extremely well shaped, rising to a maximum amplitude in 4 or 5 cyles, remaining at a stable amplitude for a total of about 20 cycles, and then dropping to zero at about 30 cycles. Figure 1 shows a typical well-shaped pulse. (The radiated pulse is assumed to resemble this simple shape closely.)

REEL   36
PULSE 140

RANGE 1.10 KYD
HYDROPHONE C_N

Fig. 1   A typical well-shaped pulse.

The ship carrying the noisemaker alternately drifted and cruised past the hydrophones so as to present a large variety of aspects.   The smoothed track used for data processing is shown in Fig. 2.

The ship's position was determined by correlating fathometer, radar, transit, and travel-time measurements.   The extreme disagreement between the fixes determined by the various methods was 500 yd.   The smoothed track is estimated to be significant to ± 150 yd.

The data recorded on the Ampex was played back at half speed and recorded by a Brush penwriter.   Comparison with recordings on a high speed photographic oscillograph indicates that the Brush record is adequate (half speed yields a frequency of 148/2 or 74 cps, which is about the upper frequency limit of the Brush).   The data was also played back half speed through a Gertsch filter (53-106 cps) and a Philbrick squaring and integrating circuit to obtain $\int p^2 \, dt$, which is a measure of the energy content.

The arrivals have been studied with respect to shape, energy content $(\int p^2 \, dt)$, and the fluctuation of energy content.   Unfortunately the fact that
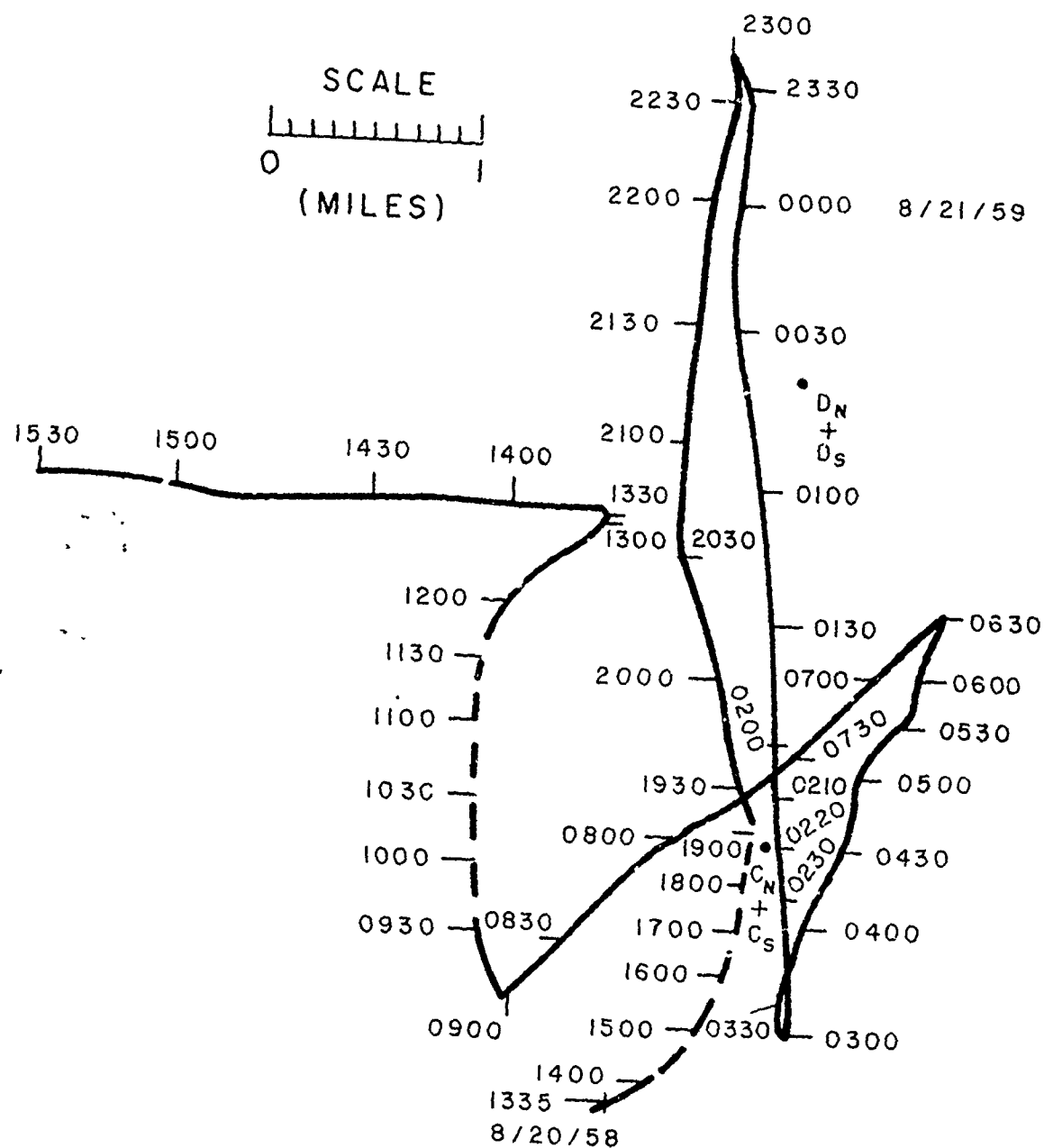
-4-

Fig. 2 Course of transmitting ship during the Bermuda operation. D_N, D_S and C_N, C_S refer to the pairs of hydrophones used in the experiment.

the hydrophones lay on a rough bottom makes it impossible to be certain that some of the observed effects are not due to the rough bottom, rather than conditions within the water or at the sea-ai. .aterface. Nevertheless, since the hydrophones lay on a 20-deg slope, it is assumed that effects which are relatively independent of aspect are not primarily due to the bottom.

Results

The discussion is based on pulses received by the C_N hydrophone. The arrivals at the three other hydrophones behaved similarly.

A destructive interference occurs when two signals, approximately 180 deg out of phase, are superimposed. Since reflection off the water surface produces a 180-deg phase shift, any two sound paths, one direct and one reflected off the water surface, that differ in travel time by n/f (where f is the frequency used and n, a small integer) will produce a minimum signal.

In this experiment many arrivals were observed which showed destructive interference. Figures 3A, B, C, and D are typical of what we have labeled very strong, strong, medium, and weak destructive interference. All four patterns were taken within a few hundred yards of each other in an area of strong destructive interference.

Figure 4 shows the degree of a destructive interference as a function of range. Since Fig. 4 is a composite of four passes near the hydrophone, the compact grouping of the data is an indication of the accuracy with which the track is known.

Figure 5 also indicates the location of the interference zones. Here they show as regions of low intensity level and high intensity fluctua-
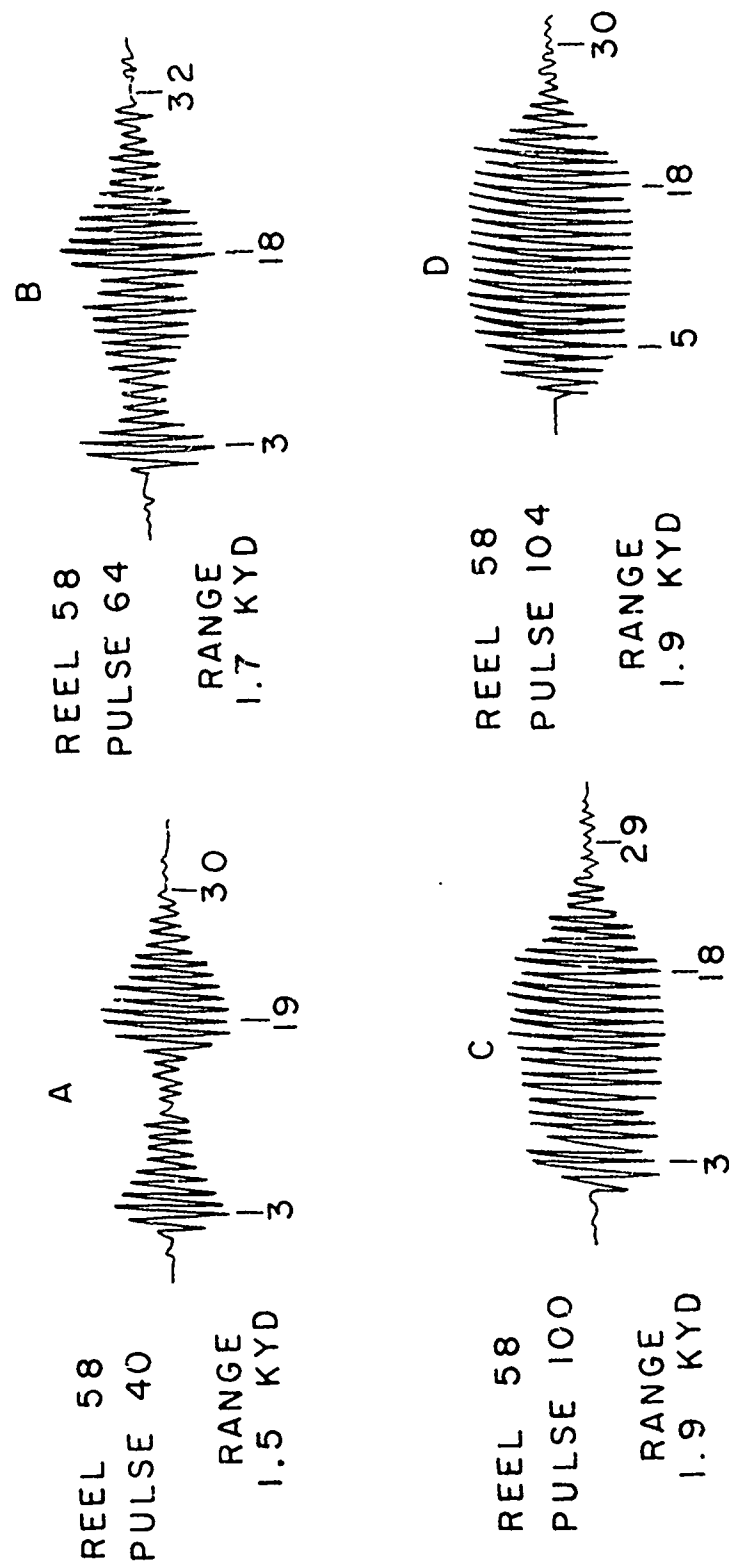
A

REEL 58
PULSE 40

RANGE
1.5 KYD

3   19   30

B

REEL 58
PULSE 64

RANGE
1.7 KYD

3   18   32

C

REEL 58
PULSE 100

RANGE
1.9 KYD

3   18   29

D

REEL 58
PULSE 104

RANGE
1.9 KYD

5   18   30

Fig. 3   Examples of pulse shapes resulting from: A. Very strong destructive interference
B. Strong destructive interference
C. Medium destructive interference
D. Weak destructive interference

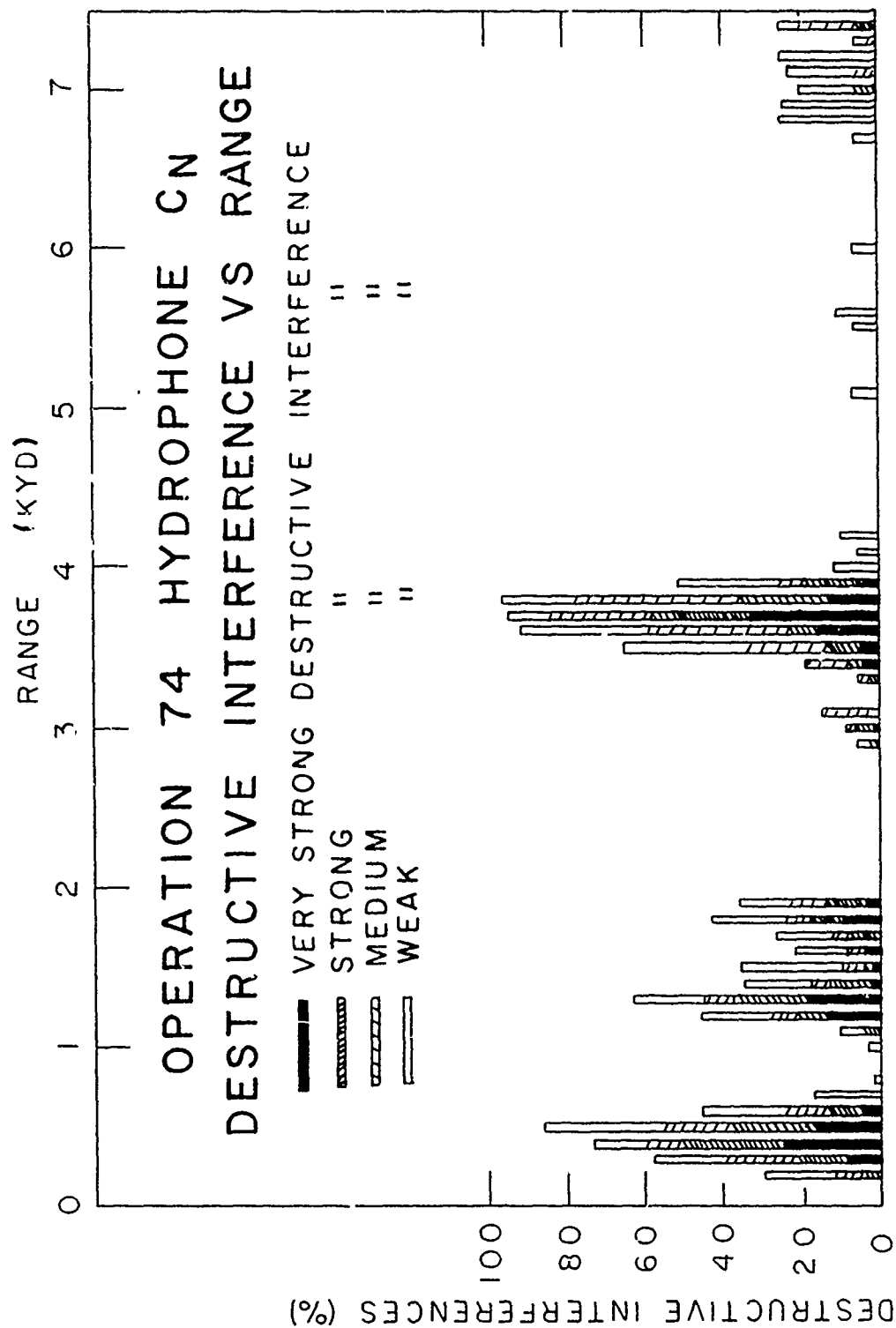Rise time, time until falloff, and total pulse length are given in terms of number of cycles.

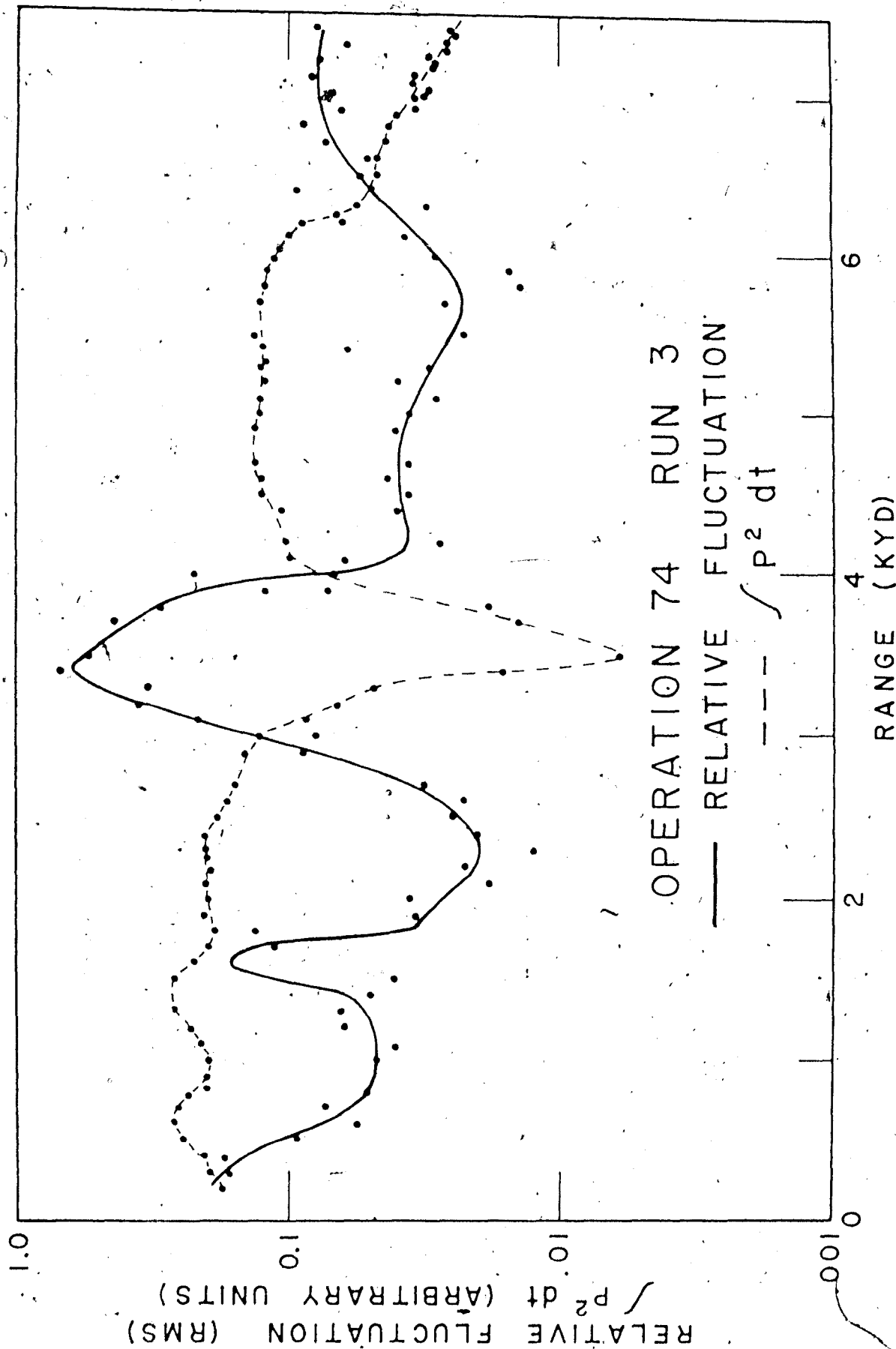OPERATION 74 HYDROPHONE C_N
DESTRUCTIVE INTERFERENCE VS RANGE

Fig. 4

OPERATION 74 RUN 3

—— RELATIVE FLUCTUATION

- - - $\int P^2 \, dt$

RANGE (KYD)

RELATIVE FLUCTUATION (RMS)
$\int P^2 \, dt$ (ARBITRARY UNITS)

FIG 5A. INTERFERENCE ZONES

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OPERATION 74   RUN 8

—— RELATIVE FLUCTUATION

--- $\int P^2\, dt$

FIG 5B. INTERFERENCE ZONES

RANGE (KYD)

$\int P^2\, dt$ (ARBITRARY UNITS)

RELATIVE FLUCTUATION (RMS)

OPERATION 74 RUN 8
—— RELATIVE FLUCTUATION
- - - ∫ P² dt

RANGE (KYD)

FIG 5B. INTERFERENCE ZONES
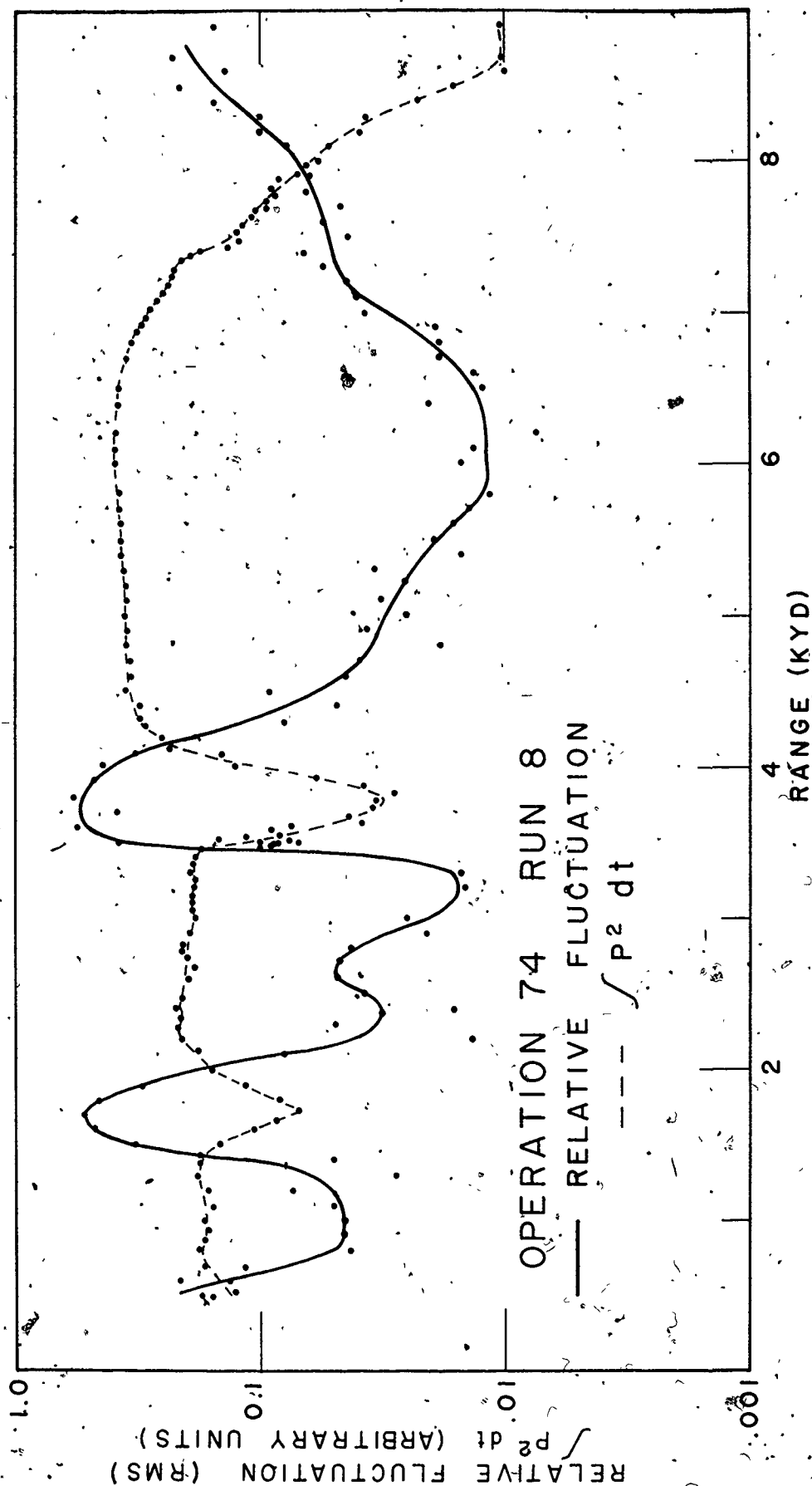
RELATIVE FLUCTUATION (RMS)
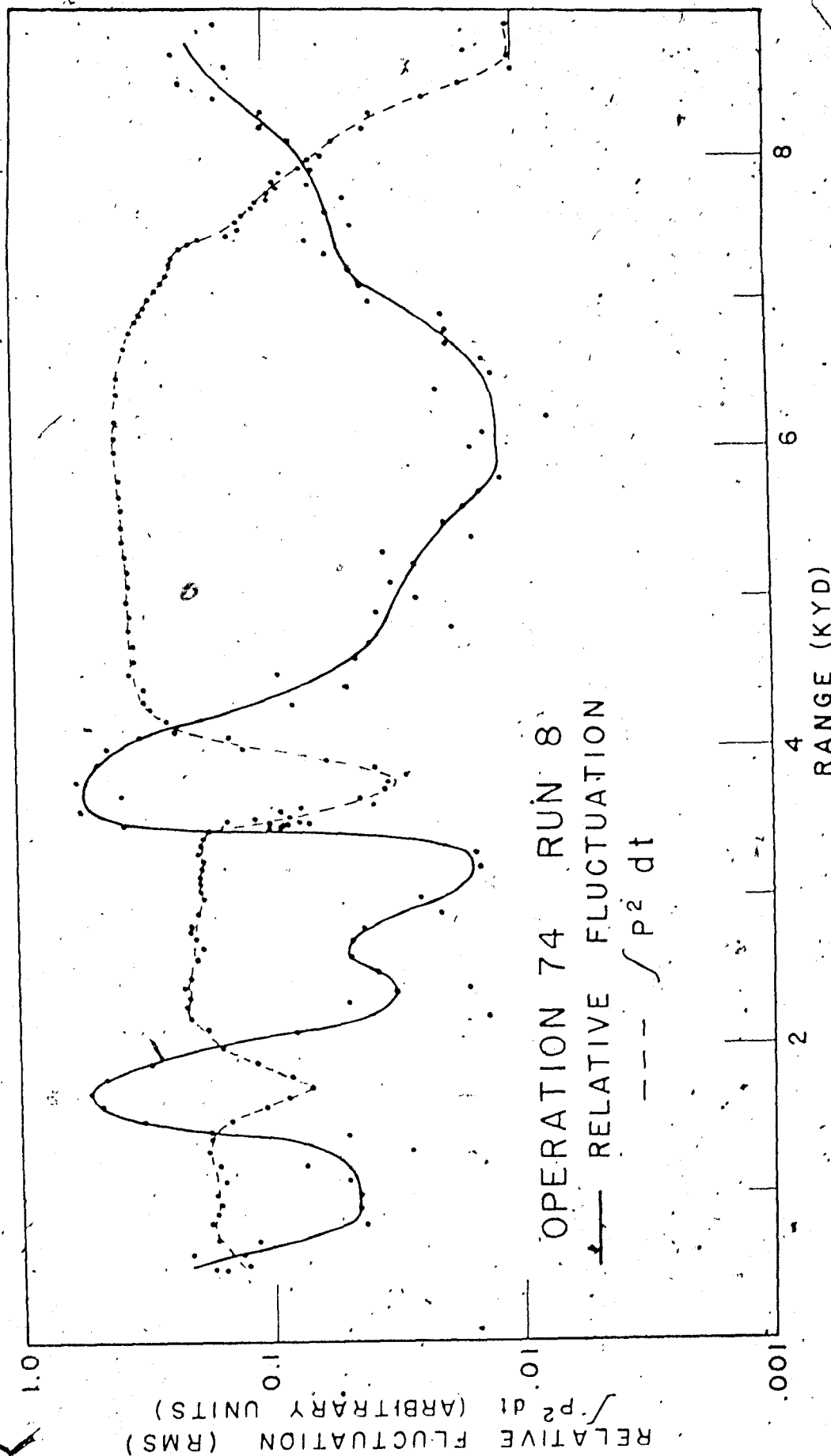∫ P² dt (ARBITRARY UNITS)

tion.* (Each "run" extends from a point of closest approach to a point of greatest separation from hydrophone C_N.) Runs 3 and 8 represent the two longest consecutive records and also, respectively, the worst and best correlations between signal level and signal fluctuation.

Assuming that the water is homogeneous with a sound velocity of 4970 ft/sec, and that the range of 500 yd as read from Fig. 4 is precise, one calculates that the source was at a depth of 53.3 ft. The nominal depth was 55 ft, as measured by the depth gauge. The 500 yd corresponds to a path difference between the direct and reflected rays of 3λ. The calculated ranges for 2λ and λ are 1630 yd and 3970 yd. These figures are too high to fit the observed values, which were 1500 yd and 3700 yd, respectively.

On the chance that these discrepancies might be due to refraction, a ray tracing was made using the Bermuda velocity and temperature profiles obtained on this experiment. Figure 6 shows velocity and temperature plotted against depth. This structure was obtained as follows: Bathythermograph records taken at the time of the experiment and extending to a depth of 900 ft were fitted to deeper data.[9] From these ray tracings interference minima were predicted for 500 yd, 1540 yd, and 3300 yd. The first two values fit very well. The last is too small. The range of this interference region, as determined in three successive passes, was 3.5 kyd, 3.5 kyd, and 3.75 kyd. The first and second passes are long by 200 yd, and the third by 450 yd. The discrepancy may be due to errors of navigation and a wrong choice of velocity profile.

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* The methods for determining intensity levels and fluctuations will be described in more detail in the second of these reports.
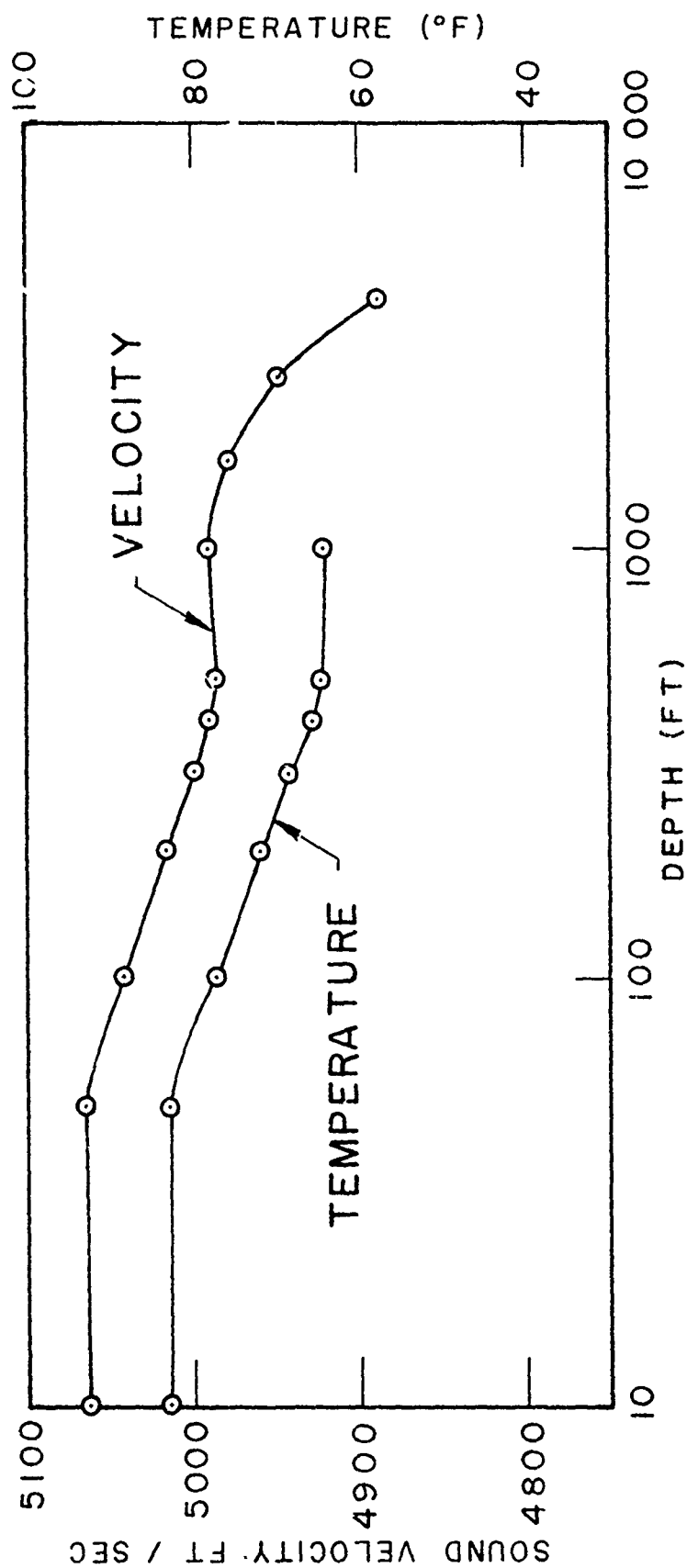
Fig. 6   Velocity and temperature plotted against depth.

Figure 7 shows a typical sequence of three pulses within a destructive interference region. Pulse 85 shows strong destructive interference, but the almost completely destructive portion is of short duration. Pulse 86 shows only a rather weak destructive interference. On the other hand, Pulse 87 shows complete destructive interference for the greater part of the pulse length.

Outside the zones of destructive interference the interference patterns resulting from the superposition of the direct and surface-reflected beams change gradually in a systematic way. At close ranges the received pulse is well shaped, showing a rapid rise to a maximum amplitude which remains stable for the number of cycles transmitted, or in some cases for a few additional cycles, after which the pulse falls rapidly to zero. As the range increases from 3 to 8 kyds, the square symmetric shape gradually decays, the rise becomes less steep, and the top less flat. Figure 8 shows very well the effect of increase in range on the pulse shape.

Numbers cannot adequately describe the changes in pulse shape. However, an attempt was made. Three numbers were used to describe the pulse shape: the rise time, the time from the start of the pulse until the start of the falloff, and the total pulse length as received, all in terms of the number of cycles. These quantities are called a, b, and c, respectively. Reference to Fig. 8A will clarify the meaning of these terms, where a, b, and c have the values 4, 22, and 36.

Figure 9 shows the average rise time, time until falloff, and pulse length as a function of range. Systematic trends are apparent. To test whether these trends occur in each individual run and to determine, if possible, the causes of these trends and abrupt changes, the average rise time,

REEL 58
PULSE 85

RANGE
1.8 KYD

REEL 58
PULSE 86

RANGE
1.8 KYD

REEL 58
PULSE 87

RANGE
1.8 KYD

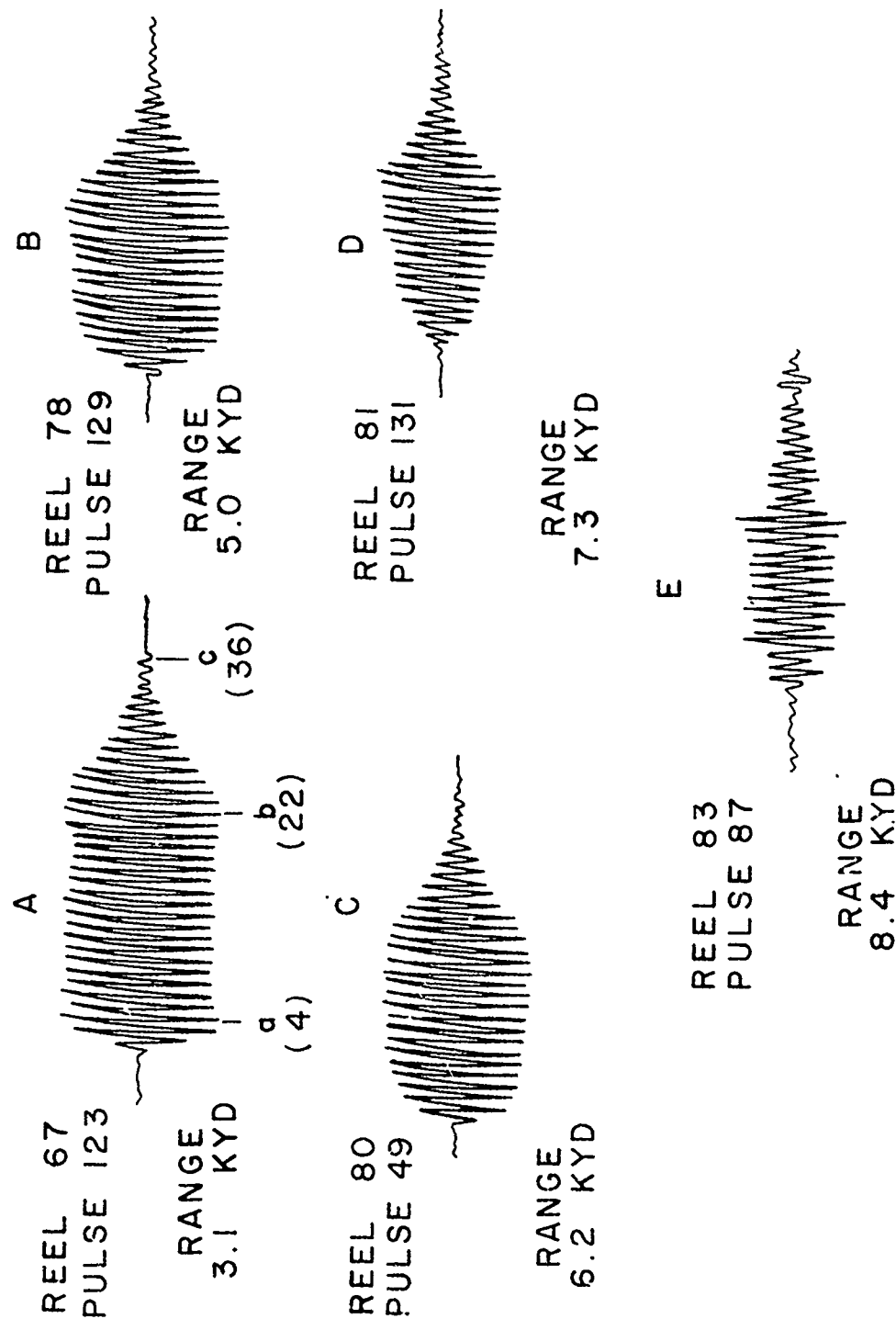Fig. 7 A consecutive sequence of patterns showing the non-systematic change of shape of the pulse.

Fig. 8 A set of typical pulse shapes showing the degrading effect of range: A. 3.1 kyd, B. 5.0 kyd, C. 6.2 kyd, D. 7.3 kyd, and E. 8.4 kyd. rise time (a), time until falloff (b), and total pulse length (c) of the pulse in number of cycles are shown in Fig. 8A.

REEL 67
PULSE 123
RANGE
3.1 KYD

a
(4)

b
(22)

c
(36)

A

REEL 78
PULSE 129
RANGE
5.0 KYD

B

REEL 80
PULSE 49
RANGE
6.2 KYD

C

REEL 81
PULSE 131
RANGE
7.3 KYD
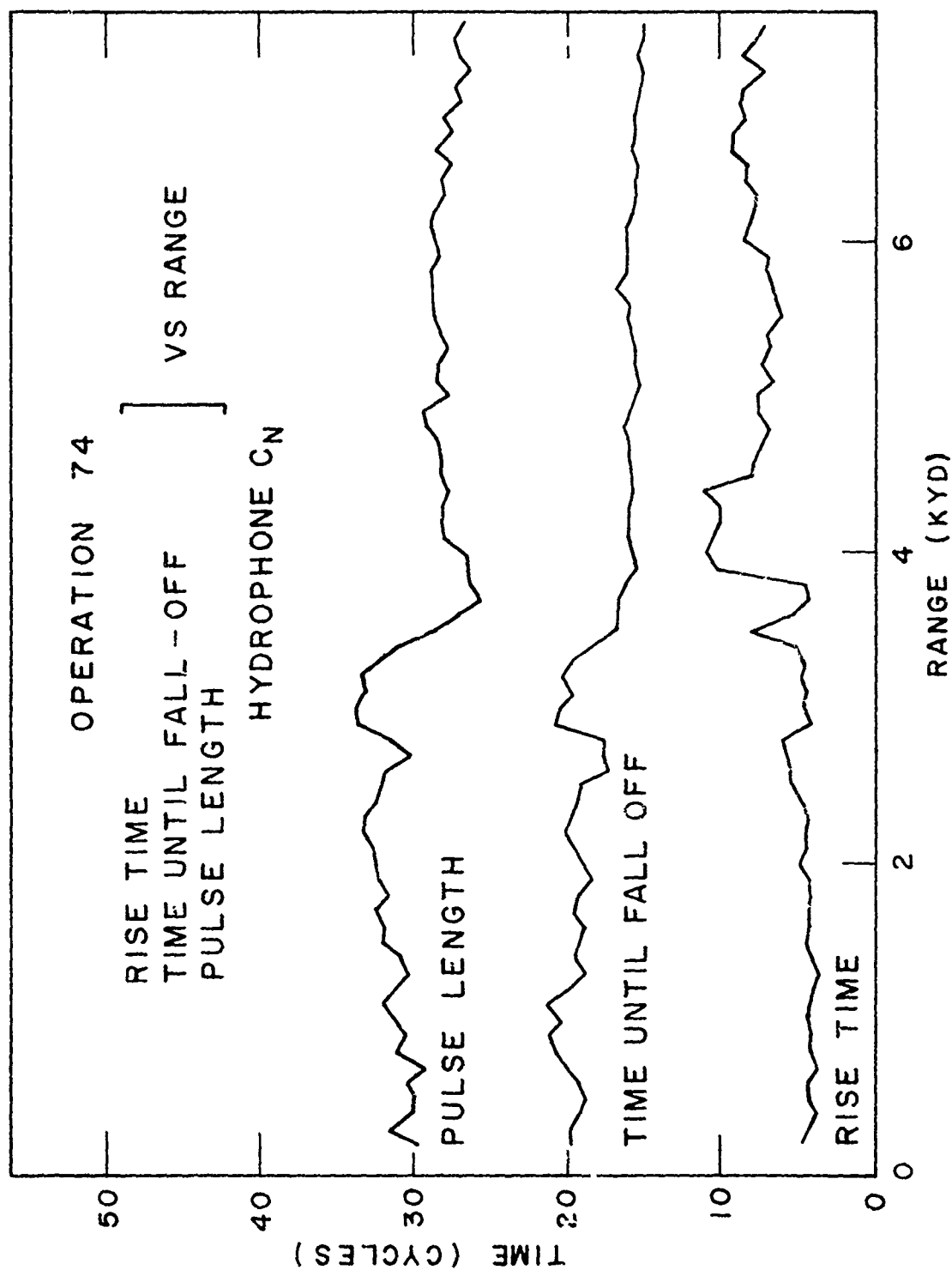
D

REEL 83
PULSE 87
RANGE
8.4 KYD

E

Fig. 9   Average rise time, time until falloff, and pulse length as a function of range.

time until falloff, and pulse length were graphed as a function of range for each of the three main runs. Each run represents a passage from 0.5 kyd or less to 7.4 kyd. Figure 10 shows these graphs. We note that although the differences between the runs may be quite great at certain ranges, the general trends are the same for all three runs. The rise times increase sharply at 3.8 kyd, only to fall very soon. The time to falloff tends to increase with range until 1.3 kyd and then to decrease irregularly out to the maximum range, where it becomes approximately the pulse length as transmitted. The pulse length from 0.2 to 3.0 kyd is about constant, but irregularities in the length tend to repeat from run to run. The length drops rapidly at about 3.5 kyd, has a slight maximum at 6 kyd, and then decreases out to the maximum range.
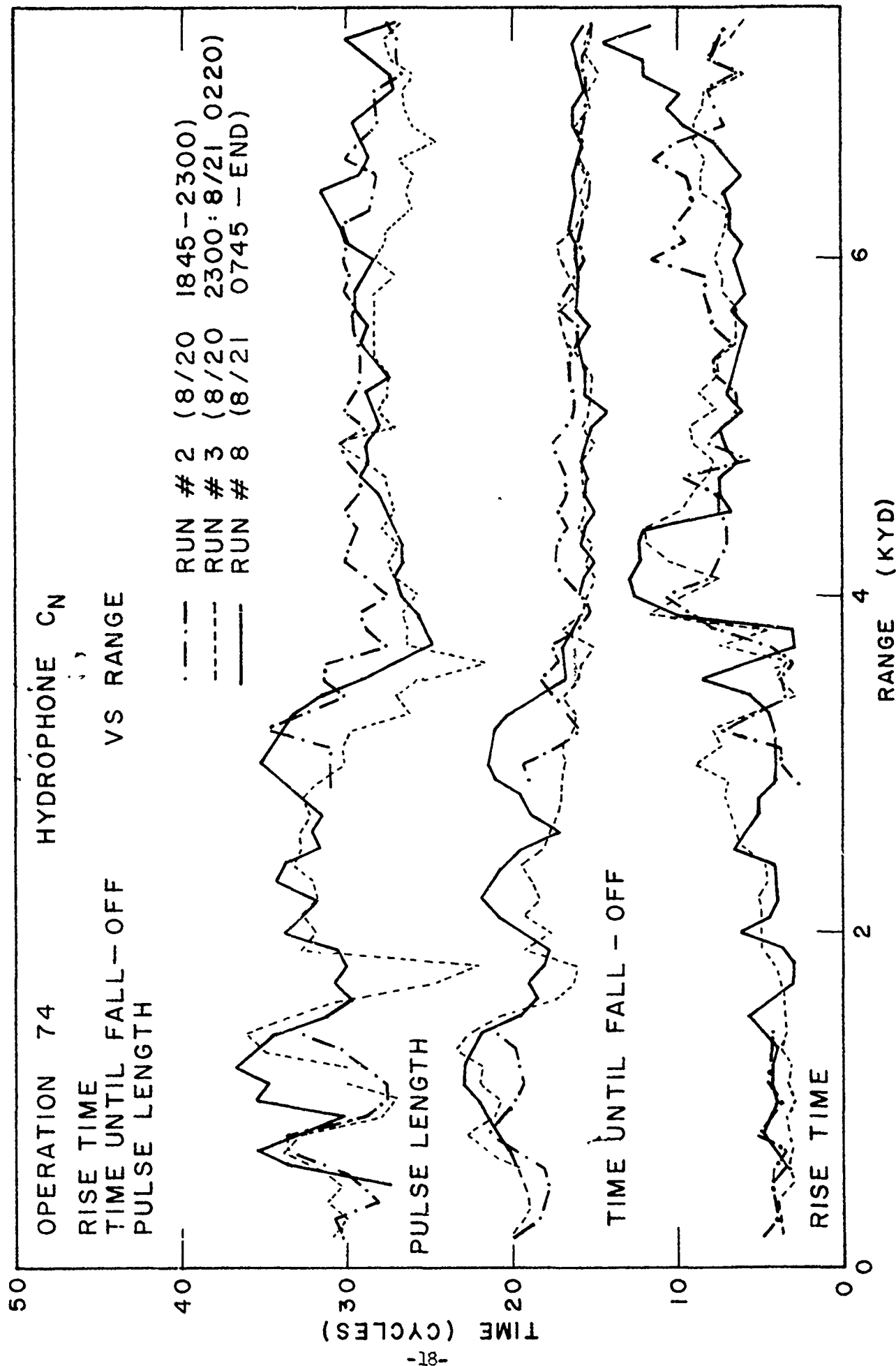
It should be noted that the rise time is shorter in a destructive interference region than in other regions. This is probably due to the definition of rise time used for computation: rise time is the number of cycles until the pulse either flattens out or starts a temporary fall. Note that the rise time increases very strongly for ranges slightly greater than the range for the 1-λ interference. There is some correspondence also between the destructive interference regions and time until falloff and pulse length.

The arrivals do not show large erratic phase (frequency) changes. Therefore, it is probable that the rapid changes in the appearance of the interference patterns in destructive areas are due to erratic changes in the amplitude of one or both of the component arrivals.*

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* F. H. Fisher (1960) reports little correspondence between amplitude and phase shift in 5-kc pulses. [10]

Fig. 10 Average rise time, time until falloff, and pulse length as a function of range for each of the three main runs.

OPERATION 74   HYDROPHONE C_N

RISE TIME
TIME UNTIL FALL—OFF   VS RANGE
PULSE LENGTH

RUN # 2 (8/20 1845—2300)
RUN # 3 (8/20 2300: 8/21 0220)
RUN # 8 (8/21 0745 — END)

PULSE LENGTH

TIME UNTIL FALL — OFF

RISE TIME

TIME (CYCLES)

RANGE (KYD)

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Discussion with Relation to Later Experiments

The results of later experiments (Op. 81 and Op. 91) yield a good qualitative explanation of the relation between signal level and signal fluctuations. An examination of separated direct and reflected arrivals shows that direct arrivals are very stable in shape and amplitude. However, the reflected arrivals show relative fluctuations which decrease as the angle of incidence increases. At 30-deg incidence the relative fluctuation in the reflection of a 182-cps signal is of the order of 20 percent (January 1959).

If stable and unstable signals of roughly equal average amplitude are added in phase, the sum will be fairly stable. However, if they are added 180 deg out of phase, the signal received is almost solely the difference in amplitude. Thus the interference pattern is very erratic, and the relative fluctuation should approach 100 percent. These predictions fit the observations very closely.

The data will not fit a simple dipole model consisting of a source and a single stable image. Such a model does account for the rough location of the areas within which destructive interference will be observed. But the random intermixing of large and small amplitudes and the widely varying envelope shapes require an unstable image.

The dipole model predicts that the rise time should decrease with range as the phase difference of the direct and reflected arrivals decreases. (A full 3-cycle decrease is expected between zero range and infinity—effectively 7000 yd.) The reverse is observed. This could be accounted for by assuming that the envelope of the reflected pulse tends to lose its flat top and to become more and more rounded as the angle of incidence increases. The large and abrupt increase in rise time at the third interference minimum is

neither expected nor explained.

The dipole model assumes that the time until falloff should also decrease with range. The effect is in the right direction but is three times as large as expected. Again, rounding of the reflected pulse would yield qualitative agreement.

The pulse length should also decrease by the same amount (3 cycles), but it increases instead out to the third interference minimum, at which point it suffers a large decrease. A further decrease with range should be expected as the signal recedes into the background. This was not observed. This could be accounted for by assuming that the process of reflection prolongs the pulse.

Later experiments in which the reflected pulse is separated from the direct do show that the reflection process tends to round the sharp shoulders of the transmitted pulse. However, this rounding often occurs at normal incidence and the effect of increasing the angle of incidence has not been investigated statistically.

There is no information available at present as to possible prolongation of the pulse by reflection. Such measurements have a top priority in current plans.

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